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Wind turbine reliability analysis

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ABSTRACT

Against the background of steadily increasing wind power generation worldwide, wind turbine manufacturers are continuing to develop a range of configurations with different combinations of pitch control, rotor speeds, gearboxes, generators and converters. This paper categorizes the main designs, focusing on their reliability by bringing together and comparing data from a selection of major studies in the literature. These are not particularly consistent but plotting failure rates against hours lost per failure reveals that problems with blades and gearboxes tend to lead to the greatest downtimes. New, larger wind turbines tend to fail more frequently than smaller ones so condition monitoring will become increasingly necessary if levels of reliability are to be improved.

Contents

1. Introduction

Interest in renewable energy has been increasing since the first oil crisis in 1973 and the renewable energy industry has made significant advances since the protocol of Kyoto (Japan, 1997) where collective reductions in greenhouse gas emissions were agreed and various developments were encouraged by governments around the world. This set the scene for renewable energy to start building market share in electrical power generation [18] and in 2007 the European Union (EU) published the "*Renewable Energy Road Map. Renewable energies in the 21st century: building a more sustainable future*". The Commission proposed setting a mandatory target of 20% for renewable energy's share in the EU by 2020, with wind energy supplying 14% [38]. Four years later the Energy Roadmap 2050 was suggesting that wind energy might supply between 31.6% and 48.7% of Europe's electricity [39], the lion's share of the market.

The wind energy industry has certainly responded. Some 39% of new capacity installed within the EU in 2009 was wind turbines [42] and wind power now provides about 6.3% of its electricity [40]. In 2011, world wind energy capacity was 237 gigawatts (GW), having been more than doubling every 3 years, and one forecast is for world wind energy capacity to rise to at least 1000 GW by 2020

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as shown in Fig. 1. World wind energy capacity has been increasing year by year and is expected to continue increasing [19].

All this has been achieved by building larger and larger WTs over the past 30 years, from 50 kW machines in late 1990s to 6 MW turbines at present. Over the same period, tower heights, rotor diameters and overall weights of turbines have almost quadrupled in size and capacity, increasing the complexity of construction, operation, maintenance and inspection procedures; 8–12 MW turbines are currently under development [16,45]. The trouble is that larger WT tend to fail more frequently and require more maintenance than smaller ones [5,10]. As turbines get larger, operating and maintenance costs can be expected to rise unless reliability is improved through condition monitoring [20]. This paper is thus concerned with:

- categorizing the main different types and configurations of WTs that have been in use since the late 1990s;
- demonstrating the role of predictive maintenance techniques such as condition monitoring;
- identifying which WT components fail most frequently and which failures cause the most downtime;
- comparing failures rates and downtimes reported independently for different types and sizes of WT operating under various conditions across the world.

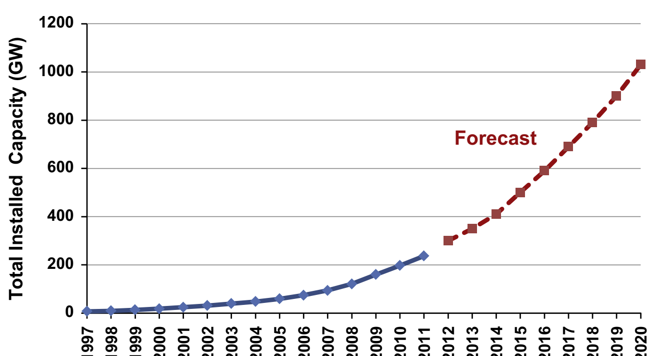


Fig. 1. Wind energy: global capacity (blue) and forecast (red). [41]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Components of WTs

Not all of the components described here will be found in every type and size of WT but the main components of a typical one are illustrated in Fig. 2. Driven by the wind, the blades (connected to the rotor by the hub) transmit the mechanical energy via the low speed shaft through the gearbox to the high speed shaft that is attached to the generator. The low speed shaft is supported by the main bearing, and the gearbox adjusts this speed; some WT configurations use a converter to match the grid connection. Alignment to the direction of the wind is controlled by a yaw system that rotates the nacelle (housing) at the top of a tower mounted on a bedplate or foundation. The pitch system (mounted in each blade) controls the amount of power going to the WT as well as acting as an aerodynamic brake; there will also be a hydraulic brake mounted on the high speed shaft to stop the WT. A meteorological unit may provide weather data (e.g. wind speed and direction) for the control of the pitch, brake and yaw systems, etc.

The costs of all these components in different types and sizes of WT will vary. For example, the costs of both converters and generators will differ depending on the configuration and some WTs do not have a gearbox at all but Fig. 3 shows the component cost distribution for a typical 2 MW WT [34].

3. WT configurations

Different configurations of WTs with innovative technology have been developed during the last few decades for increasing power. The most common configuration is the horizontal axis WT with three blades, for which different combinations of rotational speed, power control, drive train configuration and generator can be used.

The rotational speed can be constant or variable, the former only being able to operate in a narrow range of rotational speeds. At the cost of power electronic converters for adapting the output

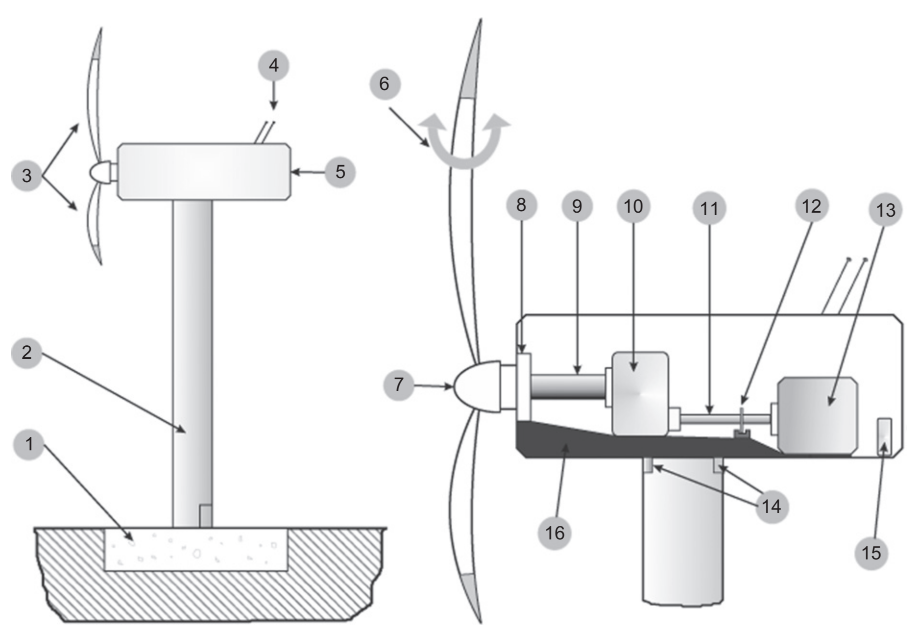


Fig. 2. Components of the WT: 1—base/foundations; 2—tower; 3—blades; 4—meteorological unit (vane and anemometry); 5—nacelle; 6—pitch system; 7—hub; 8—main bearing; 9—low speed (main) shaft; 10—gearbox; 11—high speed shaft; 12-brake system; 13—generator; 14—yaw system, 15—converter, 16—bedplate. N.B. drive train = 9 + 11.

to the grid frequency [26], the latter can be used in a wide range of wind speeds (the mechanical stresses being lower and the energy of the wind being extracted more efficiently).

Power control can be passive stall, active stall or pitch system. The blade angles in a passive stall system are fixed to the hub, the blades being designed so as to stall in strong winds. The blade angle in an active stall system is adjusted to create stall along the blades but not for increasing the wind energy captured. Stall control has been considered to be unfeasible in large WTs due to the need for emergency braking [26]. In a pitch system the blades can turn about their longitudinal axis so as to optimize the wind energy captured or, in unfavorable weather conditions, to act as a brake on the rotor; they include electric or hydraulic mechanisms that increase the cost of the WT.

The indirect drive system employs a gearbox to increase the rotational speed of the shaft that drives the generator. The direct drive configuration does not use a gearbox but needs different generators and electric power converter to adapt the energy to the grid frequency.

The main generators used in WTs are: squirrel-cage induction generator (SCIG), wound rotor induction generator (WRIG), doubly fed induction generator (DFIG), permanent magnet synchronous generator (PMSG) and electrically excited synchronous generator (EESG) [27]. Direct drive configurations use larger and more expensive generators (heavier and multi-pole) than indirect drive types.

Fig. 4 shows how the numbers and configurations of onshore installations have changed over time so as to increase the power

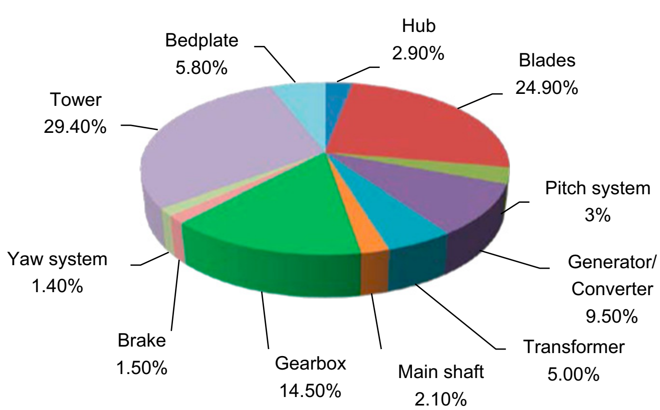


Fig. 3. Distribution of the component costs for typical 2 MW WT.

generated in Germany [23] (which had approximately 34% of the total WTs of the world in 2003 [24]) where WTs are now being installed with horizontal rotors and three blades rather than two. Pitch control and the variable speed machines have taken over from stall control with constant speed, and double fed induction generators (DFIG) seem to be replacing the synchronous ones. Nowadays a great number of different designs of WTs were developed until 2012; being WTs with DFIG the type most offered by the major manufacturers (Type C in Table 2).

Hansen et al. [26,28] identify four types of WT configuration (A, B, C and D) which may be mapped against the sub-types given by Li and Chen [29] as summarized in Table 1. Each configuration is either in service or has been so in the past.

3.1. Type A: constant speed

The rotational speed of the WT is constant and a multi-stage gearbox is used to adapt the generator to the input speed. These turbines use an asynchronous squirrel-cage induction generator (SCIG) connected to the grid through a transformer, a capacitor bank being used to compensate the reactive power that draws the SCIG. It is a common configuration in Denmark and there are three sub-types each with different means of power control: type A0 turbines use passive stall control; type A1 employ active stall control; and type A2 use a pitch control system, the most advanced technology used in larger WTs.

Rotational speed is not fixed in any of the other three configurations (B, C and D), where only the pitch system is available. The rotational speed is limited variable in type B. Types C and D have variable rotational speed and the difference is in the scale frequency converter.

3.2. Type B: limited variable speed

B type WTs use a multi-stage gearbox in combination with a wound rotor induction generator (WRIG) and a pitch control system. The power output of the system is controlled by a variable rotor resistance connected to the rotor winding of the generator. Typically, the speed control range is between 0% and 10% of the synchronous speed. The generator is directly connected to the grid, a converter being unnecessary because a capacitor bank is used instead for reactive power compensation. This configuration is called as ‘Optislip’ and it is usually installed by Vestas (Danish manufacturer).

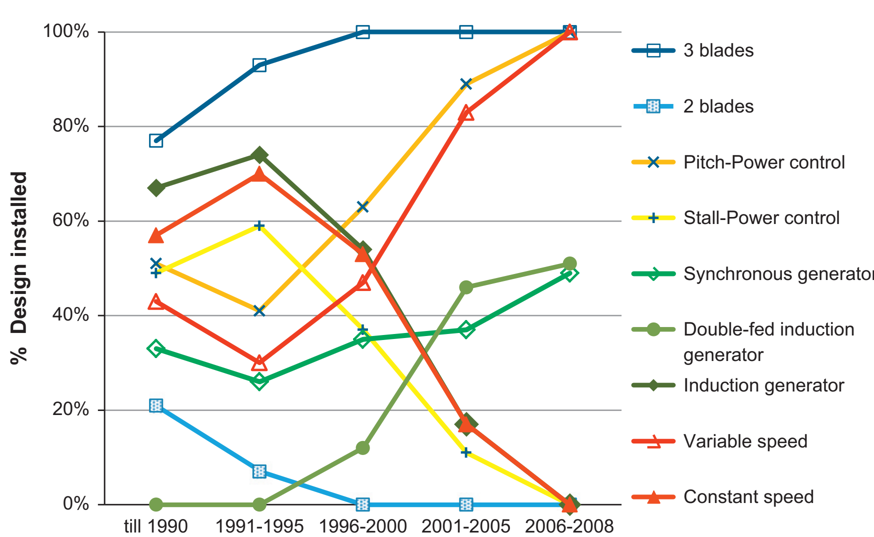
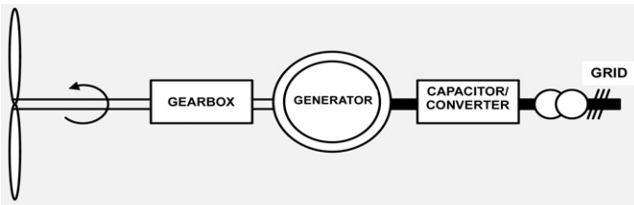


Fig. 4. WT configurations installed in Germany between 1990 and 2008.

Table 1
Configuration of WTs.



Type			Control	Speed	Gearbox stages	Generator	Capacitor/converter
A	A0		Active Stall	Fixed	3	SCIG	Capacitor
	A1		Passive Stall				
	A2		Pitch				
B			Pitch	Variable	3	WRIG with a variable resistance in the rotor winding	Capacitor
C			Pitch	Variable	3	DFIG	Partial-scale power converter. Converter feed back to the generator
D	DD	DDE	Pitch	Variable	None	EESG	Full scale power converter. Double feed back to the generator
		DDP	Pitch	Variable	None	PMSG	Full scale power converter
	DI	DI1P	Pitch	Variable	1	PMSG	Full scale power converter
		DI3W	Pitch	Variable	3	WRSG	Full scale power converter
		DI3P	Pitch	Variable	3	PMSG	Full scale power converter
		DI3S	Pitch	Variable	3	SCIG	Full scale power converter

3.3. Type C: variable speed with partial-scale frequency converter

This type has a doubly fed induction generator (DFIG), i.e. a WRIG connects the stator directly to the grid, and a partial-scale frequency power converter is attached to the rotor circuit. A multi-stage gearbox is usually used. The rotor speed range depends on the size of the frequency converter, larger ones allowing a greater range of speeds. Typically, the variable speed range is around ±30% of the synchronous speed. The partial-scale power converter takes between 25% and 30% of the nominal power output from the generator, and reactive power compensation is realized by a converter so a capacitor bank is not required (as in type B).

3.4. Type D: variable speed with full-scale frequency converter

A pitch control system sets the variable speed, and the generator is connected to the grid through a full-scale frequency converter for reactive power compensation of the input speed range. There are different configurations according to the combination of the drive train (direct-drive or indirect-drive) and generator (type and size). There are two configurations: direct-drive WTs (DD) that have gearboxes and indirect-drive (DI) that do not.

3.5. Type DD: variable speed direct drive with full-scale frequency converter

Type DD is characterized by a gearless drive train. No gearbox is used because there is a full-scale power converter with multi-pole generators. The group DDE is electrically excited synchronous generator (EESG), and the DDP group uses a permanent magnet synchronous generator (PMSG). Type DDs have a low rotor speed, and thus need larger generators and a large number of poles. Direct drives types commanded approximately 17.4% of the global WT market in 2010, and this is expected to be 24.3% by 2016 [43].

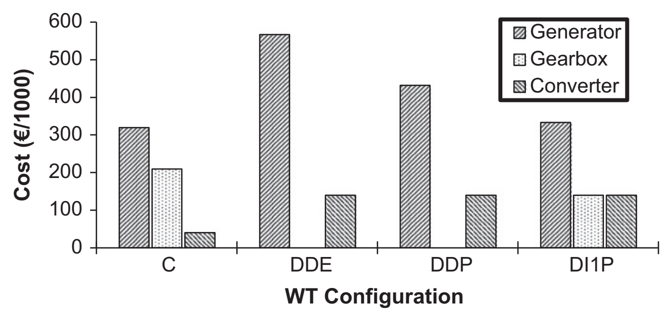


Fig. 5. Costs of selected components for some different types of 3 MW WTs.

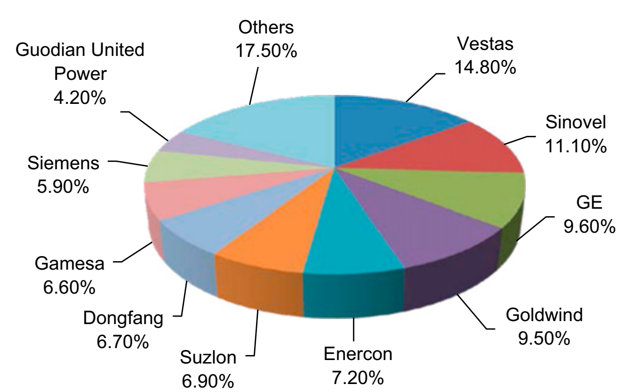


Fig. 6. Distribution of installed capacity by the main manufacturers in 2010.

3.6. Type DI: variable speed indirect drive with a full-scale power converter

Type DIs have a geared drive train and a gearbox, so larger and more expensive generators such as used in type DDs are unnecessary. Also called ‘Multibrid’, the DI1P (with PMSG) is the only configuration with a single-stage gearbox. There are fewer

mechanical components than in the various multi-stage gearbox configurations, higher rotational speed than the direct drive configurations, and smaller generators.

By contrast, most DI types have three-stage gearboxes which increase the rotor speed so as to allow smaller generators to be used than on gearless WTs. Three distinct sub-types exist: type DI3W with a wound rotor synchronous generator (WRSG); type DI3P with PMSG; and type DI3S with SCIG generator.

Based on data from [27], Fig. 5 shows that WTs with direct drive (types DDE and DDP) are expensive because of the generators required but of course they need gearboxes too. Type C is the most used and cheapest because their components are standard [27,36], but they present more failures. Type DDE is the most reliable, powerful and expensive configuration. DI1P is cheaper than DDE but it has good performance and lowest cost per unit of generated energy. Polinder et al. [37] say that DDP types are the best solution because there are no gearboxes or generator brushes to wear, and they have full frequency converters. The trend is towards full scale power converter configurations with multi-pole PMSG, i.e. types DDP, DI1P and DI3P, because they reduce losses and weigh less than types with EESG [33].

As for companies manufacturing wind turbines around the world, there are many. Commonly, they have come from other similar sectors e.g. Gamesa which originated in the automobile and aeronautical sectors and then used its technical expertise to diversify into the wind sector [19]. Fig. 6 shows the top 10 manufacturers by annual market share (installed capacity) in 2010 [32]. The presence of Chinese and Indian manufacturers has been increasing in recent years due mainly to the growth of oriental demand for wind energy. Vestas (of Denmark) is the market leader followed by Sinovel (China). Enercon (Germany), specializing in direct drive machines, is fifth.

Table 2 lists a selection of WTs from the main manufacturers, identifying the types as defined above and including the WTs analyzed in the studies presented in next sections. Manufacturers have been trying to improve the reliability of gearboxes and the technology of gearless WTs and to develop WTs of increasing power either through the same configuration (such as Vestas and Enercon) or by developing different configurations (e.g. Gamesa and Siemens).

Table 2
Characteristics and type of selected WTs from the major manufacturers including those from the studies analyzed.

Manufacturer	Model	Power (kW)	Rotor diameter (m)	Hub height (m)	Type
Vestas	V27	270	27	33	***A1***
	V39	600	39		***B***
	V44	600	44		***B***
	V47	660	47	40–55	***B***
	V90	1800/ 2000	90	80–125	***C***
	V90–3	3000	90	65–105	***C***
Sinovel	Sl1500	1500	70.4	65–80	***C***
	SL3000	3000	91.6	80	***C***
GE	GE77	1500			***C***
	GE 4,1–113	4100	113		***DDP***
Goldwind	GW70	1500	70	61,5	***DDP***
	GW90	2500	90	80	***DDP***
Enercon	E-40	600	40	46–78	***DDE***
	E-66	1500	66	67–85	***DDE***
	E-112	4500	114	124	***DDE***
	E-126	7580	127	135	***DDE***
Suzlon	S88-MarkII	2250	88		***C***
	S88	2100	88	79	***B***
Dongfang	DF82–1500	1500			***DDP***
Gamesa	G80	1800	80	60–100	***B***
	G90	2000	90	60–100	***C***
	G128	4500	128	120	***DI3P***
Siemens	B54	1000	54	47.8	***A1***
	B82	2300	82.4	80	***A1***
	B107	3600	107	80	***DI3S***
	SWT-3.0–101	3000	101	74.5–99.5	***DDP***
Guodian U. P.	UP-1500	1500	77		***C***
Neg Micon	M530	250	26	30	***A2***
	M1500	600	43	45	***A0***
	NM 72	2000		64	***A1***
	NM80	2750	80	100	***C***
Made	AE-61	1320	61		***A1***
	AE-90	2000	59		***DI3W***
Nordex	N52	800			***A1***
	N100	2500	90	65–80	***C***
Tacke	TW600	600	43	50	***A1***
	TW1,5s	1500			***C***
Acciona	AW1500	1500	70/77/82	100	***C***
	AW3000	3000	100/109/116	92–120	***C***
Multibrid	M5000	5000	116	90	***DI1P***
Nordtank	NTK300	300	28	31	***A0***
Repower	MM92	2000	92.5	68.5–100	***C***
	3.0M122	3000	122	139	***C***
Bard	VM	5000	122	90	***C***

4. WT reliability and maintenance

The high cost of the machinery and infrastructure of WTs described above, combined with the difficulty of access to them by maintenance personnel, demands complex maintenance systems if high reliability, availability, maintainability and safety (RAMS) [21,30] are to be achieved. If a bearing failure is detected, for example, the repair or refurbishment cost could be 5000 €, but, if it is not detected, this could rise to in excess of 250.000 € because of collateral damage to other components [14].

The wind power industry has thus developed significant improvements in the field of WT maintenance and repair strategies, employing condition monitoring (CM) integrated within supervisory control and data acquisition (SCADA) systems. Fault detection and diagnosis (FDD), CM and fault detection algorithms are used to provide early warning of structural, mechanical and electrical defects, enabling wind farm operators to carry out predictive maintenance and hence reducing failure rates [20]. Predictive maintenance is also used in tandem with preventive maintenance, both being very important for offshore WTs where the maintenance personnel operate at the mercy of the weather. Larger WTs require more preventive maintenance than smaller ones [6].

Kusiak and Li [25] demonstrated that faults can be predicted with reasonable accuracy 60 min before they occur by employing a CM system. Fig. 7 shows the deterioration failure leading up to the fault, called P–F curve. There is the possibility of detection of the potential fault at point P. If the failure is not mitigated, the deterioration continues until functional failure at point F; the time between P and F is the period during which the fault can be avoided [44]. Of course some components, such as rotor blades, gearboxes and generators, have higher failure rates than others due to, for example, high wear.

The life of a new WT is around 20 years and WT failures are commonly assumed to follow a bathtub curve [3] as shown in Fig. 8: high rates of failure will be observed both early on (period of early failures) and towards the end of life (period of wear out)

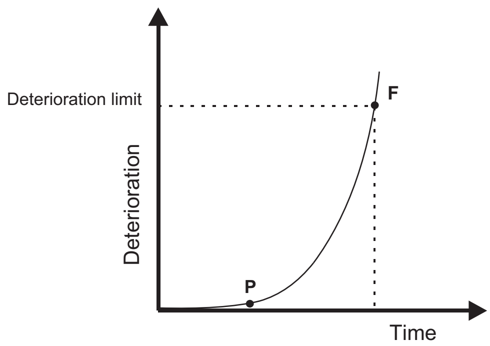


Fig. 7. P–F curve.

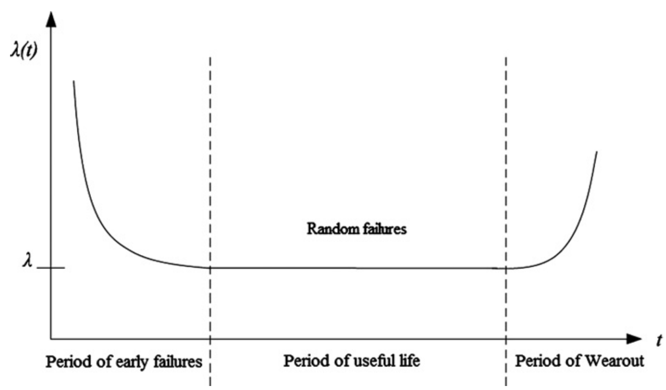


Fig. 8. Evolution of failure rate over the life cycle of a WT.

[31] but with lower rates in the middle (period useful life). Tavner et al. [3] presented data from German turbines operating in their periods of early failure and Danish ones in their periods of useful. They failed to find any data for wear out periods because the WTs were relatively new and because WTs that lose reliability tend to be taken out of service before wear out. Periods of early failure appear to be getting longer [35].

However, the average failure rate typically reported will be the number of failures per turbine per year i.e. [22]

$$f = \frac{\sum_{i=1}^{I} N_i}{\sum_{i=1}^{I} X_i T_i}; \tag{1}$$

where f is the failure rate [failures per turbine per year], N_i number of failures that occurred during the time interval T_i, T_i time interval (I in total of 1 year each one), X_i number of WTs reported for the time interval T_i and I is 1, 2,…, I (years).

In similar vein, downtime is the time during which a WT is not operating because of a fault, typically comprised of time for [22]

- diagnosing the failure (in the case of non-condition monitoring systems),
- gathering repair equipment and spare parts,
- accessing the mechanism, and
- repairing and restarting the WT (usually the longest);

and calculated by [22]:

$$d = \frac{\sum_{i=1}^{I} d_i}{\sum_{i=1}^{I} X_i T_i}, \tag{2}$$

where d is the downtime due to failures per WT per year [hours per turbine per year] and d_i productive hours lost during the time interval T_i due to failures.

5. WT component failure analysis

Various studies have been conducted in order to collect WT reliability data, including ones in Germany, Denmark, Sweden and Finland. The data are presented in different formats (e.g. failure distributions, downtime distributions (%), failure rates as failures per turbine per year, downtime as hours lost per component per WT per year) and are from different locations, weather conditions and types of WTs and with a range of operational life. Among these, Tavner et al. [17] showed that weather and location are factors in the reliability of the WTs due to the wind speed. In 2010 Tavner et al. [15] demonstrated that a significant cross-correlation exists between the failure rate and the weather conditions; temperature and humidity were more significant than the wind speed.

Within the Dutch offshore wind energy converter program (DOWEC), Bussel and Zaaijer [1,13] used a group of experts to analyze a set of WT failure data sources and obtain estimates of failure rates for WT components located in northern Germany. The blades/pitch, the control system and the gearbox accounted for most failures, and the onshore failure rate per WT per year was 2.20 in 2001 [1]. Rademakers et al. [12], also on the DOWEC program, studied the downtime distribution of WT components, and found that more than 85% of the total downtime was due to the blades, generator and gearbox.

Braams and Rademarkers [4] worked on the reliability of WT components in the CONMOW European project. They showed that the WT components with the highest failure rate were electric/control/hydraulic systems and blades/pitch [8], the electric failure rate being higher and gearbox failure rate lower than those presented by Bussel and Zaaijer [1,13].

Ribrant and Bertling [5] analyzed WT failures in Sweden, Finland and Germany. Data for Sweden were taken between 2000 and 2004 from an increasing number (averaging 625 and representing 95% of all turbines) of 500–1500 kW WTs from a variety of manufacturers. The average number of failures per turbine per year was 0.402, the electrical system, sensors and blades/pitch presenting proportionally more failures and larger and newer WTs ($>$ 1 MW) had higher failure rates [5,7]. Over 72 WTs in Finland (approximately 100% of them) were studied over the same period. The failure rate was 1.38 per WT per year, appearing mostly in the hydraulic system, the blades/pitch and the gears. The failures studied in Germany were collected between 2003 and 2005 from 865 WTs, between 4% and 7% of the total. Here the failure rate was 2.38 per turbine per year, mainly arising from faults in the electrical, control, sensors and hydraulic systems. Failures of electrics, control and hydraulic systems, sensors and blade were common in these countries, accounting for more than 65% of the totals. The largest downtimes were found in the gearbox (Sweden and Finland), followed by the control system in Sweden and blades/pitch in Finland. In Germany, the largest downtimes occurred in the generator followed by the gearbox.

The failure rate of the electric and control systems in Germany were in most of the cases higher than in Sweden and Finland. This could have been due to the types of WTs in Germany having more electrical components than those from Finland and Sweden. The downtime is almost the same in each component between countries except in Finland. Gearboxes and blades have the longest downtimes, more than 40% of the total downtime, principally in Finland. The gearbox is the component with the longest downtime per failure, due mainly to the difficulty of repairing the inside of the nacelle, and the electric system has the highest failure rate. Ribrant [7] pointed out that the gearbox is the most critical for WT availability. Hydraulics and blade systems have high failure rates and long downtimes, especially in Finland, the time required to repair or refurbish blades being great. Generators and electrics have low failure rate, but significant downtime. Conversely,

control systems yield the highest cumulative failure rate but low cumulative downtime distribution due to quick repairs and refurbishments. The main four failures from Ribrant's studies are similar to those found by Braams and Rademarkers [4].

McMillan and Ault [14] demonstrated with Windstats data from Germany that the gearbox, generator, rotor (blades, pitch and hub) and main bearing (drive train) comprise around 67% of downtime per failure. In similar vein, Spinato et al. [10] analyzed Windstats data [9] from Denmark (WSDK) and Germany (WSD) over a period of 11 years as well as WT failure statistics data from Schleswig Holstein in Germany (LWK) [11]. The electrical systems had the highest failure rates, followed by blades and control systems, but the rates were not the same in all locations (Denmark having a lower failure rate than the other two). Gearboxes caused the longest downtimes per failure, and larger WTs had higher failure frequencies [10] and hence longer downtimes and higher costs [20].

The average failure rates for WT components from references [1,7,5,10] is shown in Fig. 9. Considering the cumulative failure rate of each component, the control system has the highest value, followed by the blades/pitch and then the electric system. Gears, yaw system, hydraulic, brake, generator, sensor and others form a group with medium cumulative failure rate. Hubs, drive trains and structures all have low rates.

The study by Bussel and Zaaijer [1,13] shows that the blades present the highest failure rate of 0.72., i.e. one blade on any given WT will on average fail around three times in four years, this being excessive. Other references report WT failure rates due to blades of around 0.2 i.e. once every five years. Bussel and Zaaijer's work

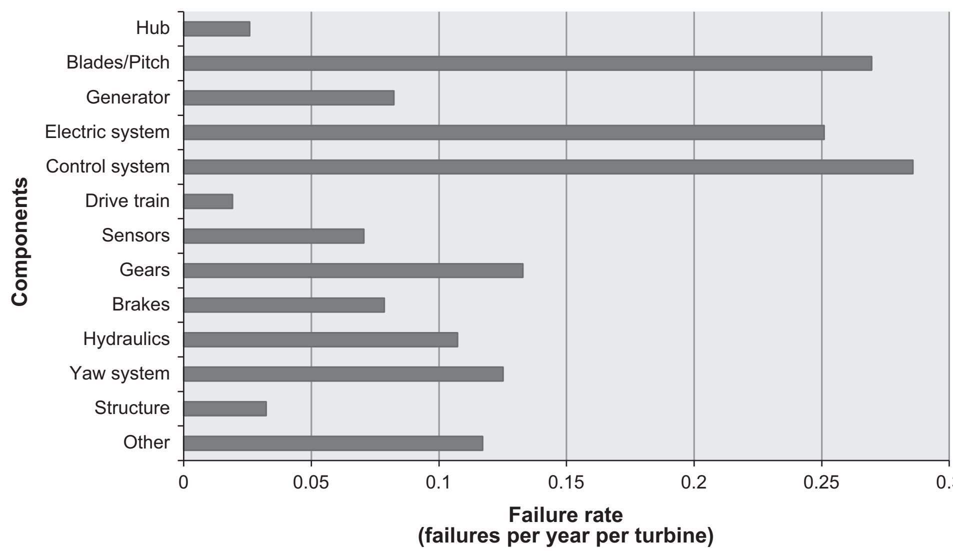


Fig. 9. Average rate of failure vs. WT components from [1,7,5,10].

Table 3
Review of failure studies in WTs.

Study	Source	Country	Average number of WTs	Study Period	Top 3 failure rates	Top 3 downtime
Bussel and Zaaijer [1]	Estimation of expert judgement in DOWEC project	DEU	–	–	Blades Control gearbox	Blades Generator gearbox
Braams and Rademakers [4]	CONMOW project	DEU			Electronic Control hydraulics	–
Ribrant and Bertling [5,7]	Elforsk and Felanalys	SWE	625	2000–2004	Electric Sensors Blades/pitch	Gears Control Electric
	VTT	FIN	72	2000–2004	Hydraulics Blades/pitch Gears	Gears Blades/pitch Hydraulics
	ISET	DEU	865	2003–2005	Electric Control Sensors	Generator Gears Drive train
McMillan and Ault [8]	Windstats	DEU			–	Gears Generator Blades/pitch/hub
Spinato et al. [10]	Windstats (WSDK)	DNK	851–2345	1993–2004	Control(converter) Blades/hub Yaw system	–
	Windstats (WSD)	DEU	1291–4285	1993–2004	Electric Blades/hub Control(converter)	–
	LWK	DEU	158–643	1993–2004	Electric Blades/pitch/hub Control(converter)	Gearbox Electric Generator

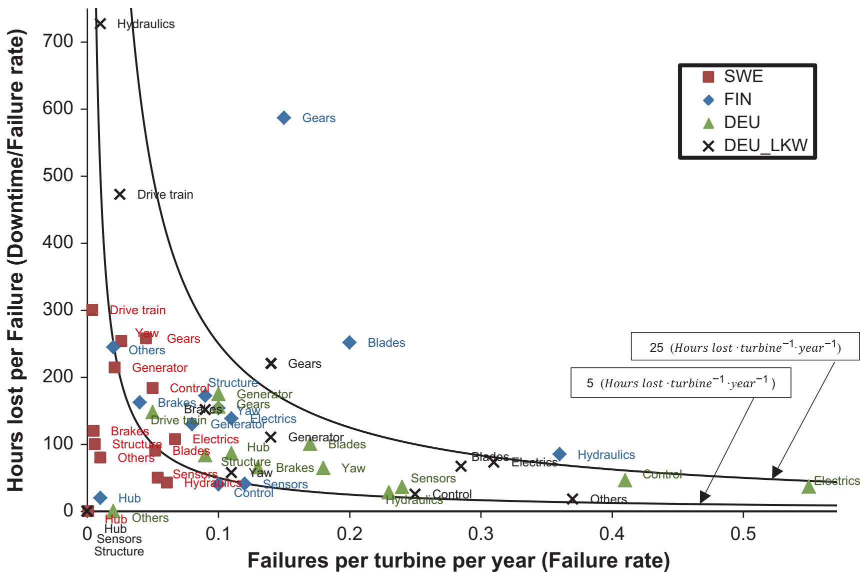


Fig. 10. Rate of failure vs. hours lost per failure: Sweden (SWE), Finland (FIN) and Germany (DEU) from Ribrant et al. and Germany (DEU_LKW) from Spinato et al.

suggested that control systems had 0.66 failures rate per turbine per year in Germany, whereas the corresponding result found by Ribrant and Bertling [5] was 0.41. Electric systems fail more frequently in Germany than in Finland, Denmark or Sweden. Gearboxes, with a failure rate of 0.3 in Germany [1] present the maximum rate. The failure rate of the hydraulic system is higher in Finland than in Germany, and the minimum rate is found in Sweden [5]. None of these authors could find failure rates in other main components because either there are no statistics or they are considered within the components described above, e.g. Spinato et al. [10] considered rotor failure rate as the failures rates of blades and hub combined. The components with the top three failure rates and downtimes are collected in Table 3. Blades, control and electrics are the components with the highest failure rates; gearboxes, generator and blades cause the most downtime.

An alternative way of viewing these studies from Sweden, Finland and Germany [7]—and indeed the other data from Germany [11]—is to plot failure rates against hours lost per failure for each of the different components as shown in Fig. 10. Note that hours lost per failure were actually calculated from downtime per turbine per year divided by failures per turbine per year, and that the two curves superimposed upon the plot are lines of equal downtime (5 and 25 h lost/turbine per year) so as to separate the data into three groups as follows.

i. Components which fail frequently or that cause long downtimes per failure and hence cause more than 25 h lost/turbine per year, i.e. gears, blades and hydraulics in Finland, as well as gears from Germany (DEU_LKW);
ii. Combinations of failure rate and downtimes per failure that lead to between 5 and 25 h lost/turbine per year, e.g. all generators, yaw systems, control systems and electrics;
iii. Infrequent failure and low downtime resulting in less than 5 h lost/turbine per year e.g. all hubs and sensors except ones from Germany (DEU).

6. Effect of type and power

Koutoulakos [22] presented a study of WTs in Schleswig Holstein (LKW) Germany. The WTs were horizontal axis machines, having three blades, yaw systems and generating 600 kW, those of type DDE having the largest sum of failure rates followed by A1, B and A0 (Table 4). Table 5 shows the downtime, where type B has the longest availability followed by A0, DDE and A1. Some WT types do not incorporate certain components, i.e. A0 does not have a pitch system or converter, and DDE does not have a gearbox (the generator being attached to the rotor) but it has a converter with sophisticated power electronics and also synchronous multi-pole generator, so electrical failures in DDEs are more frequent.

Blade failure rate is the same in most of the WTs, but the downtime in the A1 type is higher due to them having active stall control systems. Pitch failures arise more in type B and mainly in DDE (Tables 4 and 5). Type A0 has failures in the aerodynamic brake due to the passive stall of this configuration. The gearbox failure rate is similar for A1 and B and higher than for A0; for DDE it is zero because of the direct drive configuration. A1 has the longest downtime, double that of type A0.

Tavner et al. [2] studied three types of WT configurations: type A1 (fixed speed indirect drive with stall control); type B (variable speed indirect drive with pitch control and WRIG) and; type DDE

Table 4
Failure rates of components for types A0, A1, DDE and B.

Components	Type & model			
	A0 Micon M1500	A1 Tacke TW600	DDE Enercon E40	B Vestas V39/V4x
Blades	0.22	0.38	0.24	0.17
Pitch	0	0	0.3	0.1
Generator	0.18	0.18	0.35	0.09
Electric	0.27	0.28	0.54	0.34
Inverter and electronics	0.2	0.14	0.31	0.27
Shaft/bearings	0.06	0.02	0.08	0
Sensors	0.12	0.07	0.12	0.08
Gearbox	0.1	0.2	0	0.18
Brake	0.05	0.18	0	0.01
Aerodynamic brake	0.1	0	0	0
Hydraulics	0.07	0.18	0.02	0.26
Yaw	0.06	0.18	0.11	0.1
Anemometry	0.02	0.04	0.08	0.06
Other	0.25	0.3	0.24	0.2

Table 5
Downtime of components of different types of WTs.

Components	Type & model			
	A0 Micon M1500	A1 Tacke TW600	DDE Enercon E40	B Vestas V39/V4x
Blades	6.5	28	16	6
Pitch	0	0	5	2
Generator	6.5	10	22	4
Electric	5	7	16	7.5
Inverter and electronics	2.5	2	7	5
Shaft/bearings	17	2	8	0
Sensors	1.5	1	2.5	1
Gearbox	14	37	0	5.5
Brake	1	2	0.5	0.5
Aerodynamic brake	2	0	0	0
Hydraulics	1	2.5	0	6
Yaw	1	4	3	2
Anemometry	0.5	1	1	1
Other	2	7	9	2.5

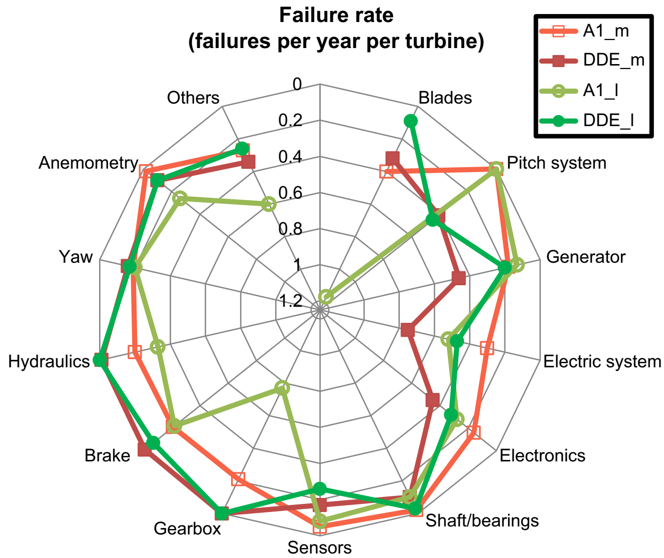


Fig. 11. Failure rate of types A1 and DDE of medium (_m) and large power size (_l).

(variable speed direct drive turbines with EESG). Their study considered two power sizes of WTs in Germany based on the LWK database. Fig. 11 shows the failure rates of types A1 and DDE of medium and large power size.

Their medium power group (500–600 kW) was comprised of 100 WTs of types A1 and B (indirect drive), and type DDE (direct drive). A1 and B medium size WTs provide more failure rates than DDE, mainly in the gearbox. Medium size DDE types exhibit more electric/electronic failures than A1 and B, the availability of indirect drive WTs being lower due to gearbox downtime. The causes of failure of components of the drive train tend to be the most numerous [2]. Medium size WTs with variable speed (type DDE in Fig. 11) have higher failure rates than types with fixed speed (type A) in electrical components (electrics, generator, electronics and converter). Only the generator failure rate is about the same in both types. Medium size WTs with variable speed present more failure rates in the control system, especially the pitch mechanism. Failure rates in the drive trains of fixed speed turbines are higher.

The large power group was comprised of 35 WTs of type A1 and DDE between 800 and 1500 kW. The generator failure rate in

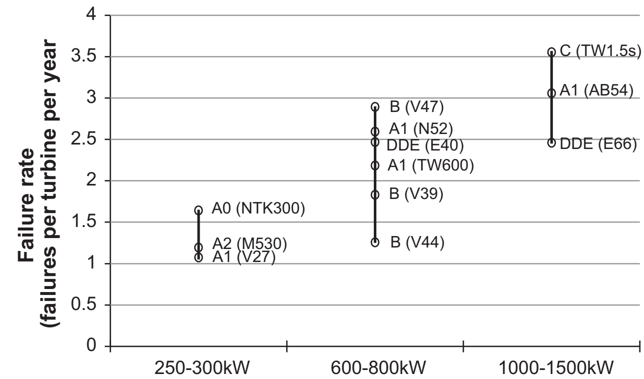


Fig. 12. Distribution of failure rates for WTs of different type and power.

large DDE types was double that of large A1 types. The A1 type has an active stall control and DDE a pitch system control. The blades of large A1 WTs have higher rates of failures, but large DDE types present pitch failures.

Fig. 11 shows that blade failure rates for larger A1 WTs are more than double those of medium size A1s. The blades, gearboxes and brakes in WTs with stall control (type A1) present more failures than in WT with pitch control ones, but the very presence of a pitch mechanism itself introduces the possibility of additional failures in DDE types.

Spinato et al. [10] presented the study summarized in Fig. 12 comparing component failure rates for various WT configurations and power. Failure rate appears generally to increase with the power of the WT although the failure rates of medium and high power DDE types are the same. Furthermore the WTs of the same type and power present different failure rate, possibly due to differences in location and/or weather conditions.

7. Conclusions

Understanding the failures rates and downtimes of WTs is difficult not only because of the considerable range of designs and sizes that are now in service worldwide but also since studies are conducted independently under various operating conditions in different countries. Nomenclature is inconsistent too, and published data is necessarily aggregated (because of not only space but also commercial confidentiality) so that straightforward comprehensive pooling is impossible. However this paper offers the following general observations having compared and interpreted a selection of recent major studies.

- The reported failure rates of hubs, generators, sensors, brakes, yaw systems and structure do not vary much between different studies. Nor do the downtimes reported for any of the major components except gearboxes, blades or hydraulics.
- Blades, control systems and electrics are most frequently cited in connection with failure rates; gearboxes, generators and blades feature most in consideration of downtime.
- Most problematic are components such as gears, blades or hydraulics with combinations of failure rate and downtime per failure that result in high downtime (hours lost per turbine per year)
- The trend is towards three blades, power control by pitch system and variable rotational speed. Type C (variable speed with partial-scale frequency converter) is the cheapest configuration and most widely used in the market.
- Direct drive (DD) WTs have more frequent electrical and electronic failures than indirect types (A, B, C, DI) but, for these, gearbox failures cause the most downtime.

- Larger WTs tend broadly to suffer more failures than smaller ones although this is confounded by type and differences between manufacturers.

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